

STEAM-FILM HEAT TRANSFER COEFFICIENTS FOR VERTICAL TUBES

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Measurement of Tube Wall Temperatures in Heat Transfer Experiments

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DETERMINATION of the temperature of tube walls is an integral part of most experimental work involving a study of heat transfer coefficients to and from these surfaces through the enveloping films. The final degree of accuracy obtained in such work is usually controlled by the accuracy of determination of the surface temperatures.

Recent important investigations concerning the condensation of vapors and heating of liquids have required more than an approximate knowledge of the wall temperatures of the experimental tubes. Some few investigators, justified by accepted data, have preferred to assume approximate heat transfer coefficients for one or another of the films rather than to carry out the work necessary for the actual measurement of the desired temperatures. Others have adopted or developed methods that have not eliminated this part of heat transfer studies as a source of considerable error. The amount of error involved in any given case can only vaguely be estimated, but it is certain that a better correlation of all such work would be possible with improved methods of measurement.

Reviews of the methods utilized have recently been made by Othmer and Coats (8) and Colburn and Hougen (4). Additional references supplementing these are included in this paper. Installations as applied to tubes alone are considered.

By far the major portion of the work done on this problem has been carried out with thermocouples, which, because of their inherent economy and flexibility of installation, may be considered the most likely instrument to be chosen. Installations of resistance thermometers (3, 7), mercury thermometers (2), portable contact recorders (1, 5), and extensimeters (9, 10) have been made. These latter methods are not generally applicable and are not to be preferred if a successful thermocouple method is an alternative.

USE OF THERMOCOUPLES

Any installation involving thermocouples should meet the following requirements:

1. The temperature recorded by any given junction must be that of the corresponding wall temperature or one from which the wall temperature may be calculated by the use of known relations.
2. The effect of heat conduction to the junction by the leads should be minimized or eliminated.
3. The characteristics of the normal film on the wall must not be disturbed by the installation.
4. Any installation should be in mutual agreement between different couples and should be capable of accurate reproduction.
5. The assembly should be sufficiently rugged to withstand all conditions encountered during installation of the tube in the test apparatus.
6. A minimum of time should be required for installation and calibration unless the permanency of the set-up warrants additional work.
7. Frequent recalibration and attention to the couples should not be necessary.

As most investigations are carried out with tubes of relatively small diameter and of considerable length, mechanical considerations will restrict the operator to the use of the outside wall of the tube. When it is necessary to contend with a vapor condensing on this wall, the problem of an undisturbed film becomes paramount, particularly with vapors of large latent heats which form very thin films of condensate. Since relatively large temperature differences occur through these thin films, any mechanical imperfection or deformation

of the natural surface in the vicinity of the couple junction that causes a penetration or distortion of the film will result in abnormal heat conduction to the junction (peened, plated, and slotted installations). If the lead wires from the junction are carried out directly into the higher temperature of the vapor space, the effect of heat conduction along the leads becomes considerable (peened and plated installations). There is no way at present by which this effect can be calculated.

No single thermocouple method developed to date, on the basis of data presented, can be said to be free from either or both of these objections, with the possible exception of the Kraussold installation (6).

The latter utilizes a longitudinal groove [0.0625 inch (0.16 cm.) deep, 0.125 inch (0.3 cm.) wide, and 6 inches (15 cm.) long]

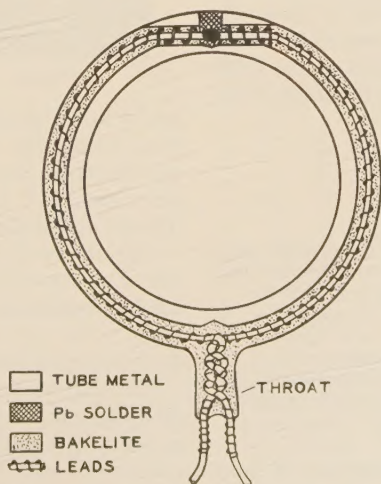


FIGURE 1. THERMOCOUPLE INSTALLATION

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milled in the tube wall. A spline of the tube material, made with a concave bottom to allow for the couple and leads, is cut to fit the groove snugly. When the spline has been driven into place an equivalent of the original surface remains. The leads are brought through the film at opposite ends of the spline and well away from the junction. It has been found extremely difficult to make even a passably good job by this method. Even if a smooth external surface is obtained, the spline has a tendency to work loose on repeated heating and cooling. Further, the leads in the Kraussold method disturb the drainage of the condensate if the tube is vertical. It is only necessary to try the Kraussold method and the one here suggested to decide which is superior.

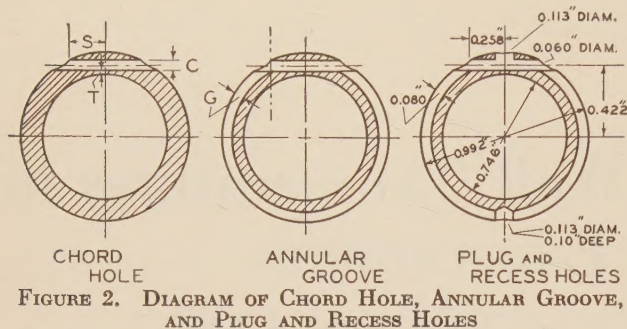


FIGURE 2. DIAGRAM OF CHORD HOLE, ANNULAR GROOVE, AND PLUG AND RECESS HOLES

Dimensions are for installation in 1-inch 11-gage tube.

The solution to both the requirements of unchanged surface conditions and freedom from abnormal heat conduction to the junction may be reached in a logical fashion. The couple junction should be placed under a surface over which the film drainage is not disturbed, and the leads must be withdrawn for an appreciable distance from the junction through a section of the wall that is isothermal with the point at which the couple is embedded.

PROPOSED METHOD

Reference to Figure 1 will illustrate the features of the method. The thermocouple is inserted in a hole drilled through a chord of the wall, and the leads are carried around the tube in an annular groove to be withdrawn at the back, 180° from the junction. The junction itself is brought into metallic contact with the wall by solder admitted through the plug hole above. Bakelite cement of special composition provides electrical insulation and fills the groove and chord hole up to the junction. The excess solder and Bakelite may be removed with fine emery cloth to produce a continuous and polished surface at all points except where the leads leave the tube, 180° from the point of measurement.

It is necessary to employ tubes of somewhat heavier walls than those ordinarily used in order to provide sufficient metal for the chord drill, which is necessarily limited as to the smallest size that can be employed. The additional metal offers no disadvantage as it is only a very small part of the total resistance to heat flow, and transfer through it can be accurately calculated.

DETAILS OF METHOD

Steps in machining are as follows (Figure 2):

CHORD HOLE. Diameter of drill chosen is dependent upon obtaining greatest distance S without causing too small a thickness at T . Drilling is done with template shown in Figure 3.

ANNULAR GROOVE FOR LEADS. Width = C , depth = G . Cut on lathe with round-nosed tool of width = C (Figure 3). Lathe is moved by hand, lifting tool over uncut section.

PLUG AND RECESS HOLES. Diameter = approximately $2 \times C$ to a convenient drill size. Recess hole is necessary to permit proper footing for lead throat of Bakelite.

Thermocouples are made from copper-constantan of most convenient wire diameter. Junction is butt-soldered with silver to give neat bead that threads through chord hole.

INSTALLATION OF COUPLES. The plug hole is first tinned. The chord hole must be packed with asbestos thread during this operation. The couple is then threaded in. To center the junction and prevent sweating of solder into the chord hole while soldering the junction, short pieces of metal tubing, that fit closely over the leads and in the chord hole, are threaded over the leads and up to the junction. The tips of these tubes should be covered with melted borax to prevent solder from adhering to them. If hypodermic needles of proper size can be found, they are the most convenient type of tubing for the above work (D , Figure 3). The couple is soldered in, using a blast lamp to maintain the tube at the proper temperature. The solder must be allowed to flow naturally into the hole and must cool slowly. Ordinary lead-tin solder is recommended as satisfactory and most easily handled. When the couple is soldered in place, each lead is hand-wrapped in two steps (E , Figure 3): First, a cotton thread, of sufficient diameter to allow only slight clearance from the walls when well smeared with Bakelite, is wrapped around the portion of the leads in the chord hole, and well packed into the holes with the tubing previously mentioned. Lighter cotton is then wrapped around the leads from the holes and carried along a distance sufficient to provide for insulation in the groove and about one inch additional. A light coat of Bakelite is then laid in the groove and on the thread, and cured. Next, the leads are brought together at the recess hole, twisted around each other for about 0.5 inch (1.26 cm.), and then carefully bent or pushed into the very bottom of the groove at all points. With successive coats of Bakelite, the groove is completely filled and a throat of supporting Bakelite is built around the twisted leads. Excess

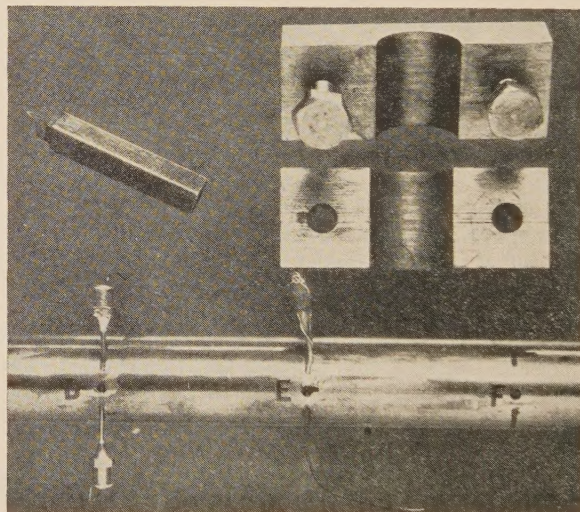


FIGURE 3. PHOTOGRAPH OF INSTALLATION

solder and Bakelite are removed, first with sand paper, and then with a fine grade of metallographic paper. The leads are joined to wires of similar composition, leading to the instruments, and proper insulation is applied to these joints. Thread and Bakelite will serve the latter purpose.

CURING OF BAKELITE. Bakelite resin BR-0013 has been found most satisfactory. This material should be mixed with kaolin or silica (200 mesh) in the proportions of two parts of resin to one part of filler. Better adhesion of the cured resin to the metal is obtained by use of the filler.

The material recommended will harden completely within 20 to 30 minutes at a temperature of 120° to 130° C. Thin coats must be applied. Curing the resin on the installations can most easily be effected by the use of an oven of special construction. This latter can be a transit box, split laterally and fitted with hinges. The ends are cut out to fit the tube

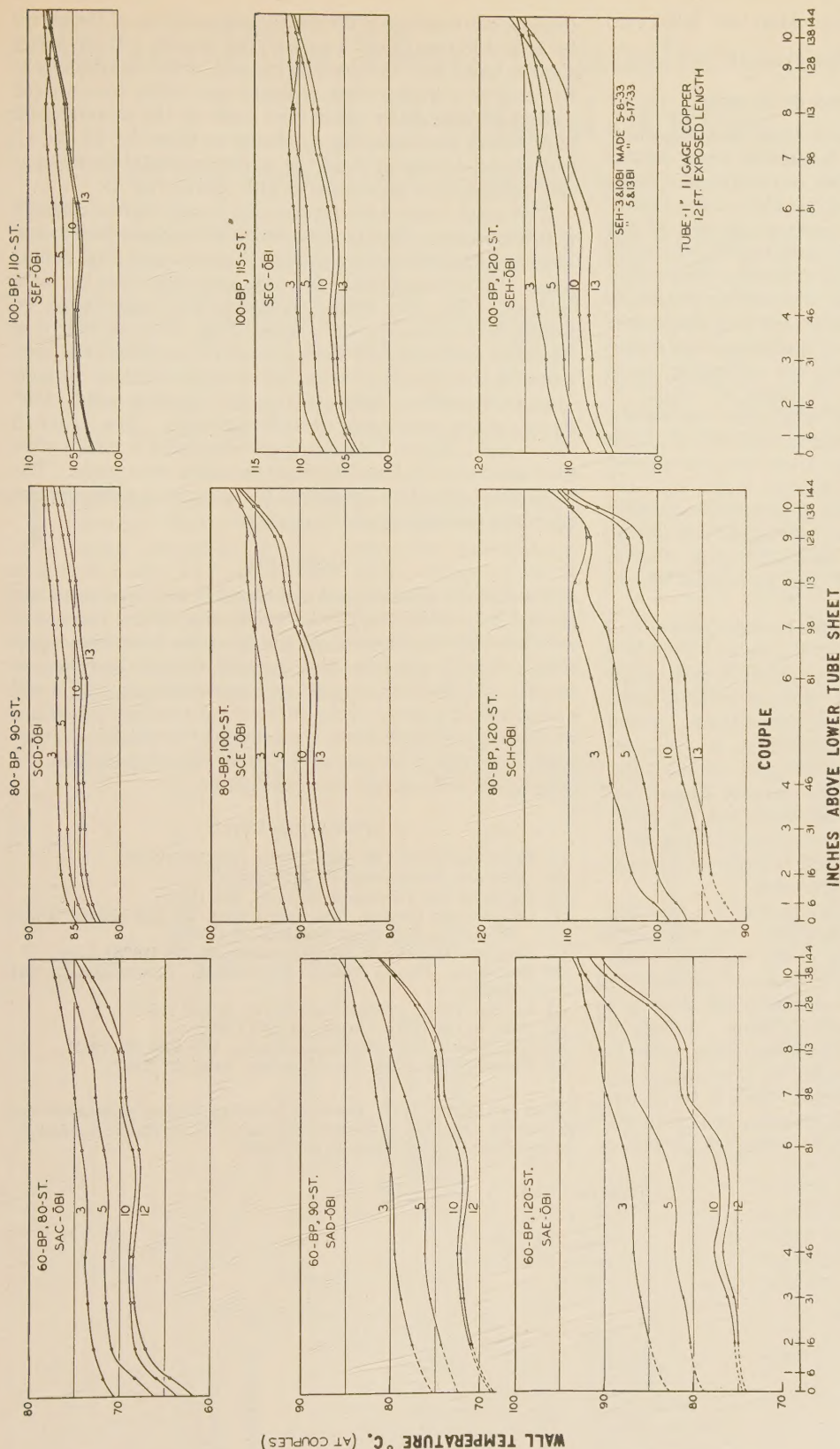


FIGURE 4. RESULTS ACHIEVED IN MEASUREMENT OF WALL TEMPERATURES

necessary will be required for curing. This difficulty may be overcome by the use of an internal heater for the tube, constructed of a short length of small-diameter iron pipe. The pipe is covered with an asbestos sleeve, wrapped with resistance wire, and then further covered with a spaced spiral wrapping of asbestos tape. This heating element is placed in the tube at a point under the junction. A moderate heat input will maintain the tube temperature at the same degree as that of the oven.

INSULATION OF LEADS THROUGH VAPOR SPACE. A satisfactory insulation of the leads through the vapor space is essential. Tests of various materials subjected to steam and hot water at temperatures of 250° to 280° F. (121° to 138° C.) for periods of 100 to 200 hours definitely proved that the usual forms of insulation are unsatisfactory. The insulations examined and found to be unsatisfactory include ordinary red rubber tubing, soft and lightly vulcanized black rubber, pure gum rubber, varnished cambric tubing (radio spaghetti), and enameled coverings. The form of insulation employed on R. C. fixture wire stood up best and suffered no apparent loss of insulating properties or any deformation. This type of covering was applied to the leads used in the investigations made in this laboratory and gave excellent service. No deterioration was found after more than 300 hours of exposure to saturated steam. These leads are flexible and may be brought out from the vapor space between flanged surfaces.

DATA FOR PRESENT INSTALLATION

Machining dimensions, see Figure 2.

Tubes: 1-inch 11-gage copper, 0.992 inch (2.5 cm.) outside diameter, 0.750 inch (1.9 cm.) inside diameter.

Thermocouple: Copper-constantan, No. 24 B. & S. wire, junction centered 0.074 inch (0.188 cm.) below outer wall.

Chord hole: No. 53 drill (0.0595 inch, 0.151 cm.).

Plug and recess holes: No. 33 drill (0.1130 inch, 0.287 cm.).

Bakelite: No. BR-0013, 2 parts, with 1 part 200-mesh kaolin.

Thread insulation: No. 20 cotton in chord holes, No. 60 cotton in grooves.

snugly. Sufficient coiled resistance wire is distributed on the inner walls of the box to maintain the desired temperature within the oven. Temperature control can be effected within the desired limits by additional series resistances. Radiation losses from the length of tube outside the box may be so high that it will be impossible to maintain a proper intensity of heat in the tube itself, and a longer period of time than is

Grooves: 0.060 inch (0.152 cm.) wide, 0.080 inch (0.203 cm.) deep.

Hypo needles: No. 17 gage, 2 inch (5 cm.) length.

EXPERIMENTAL APPLICATION OF METHOD

Preliminary trials were made in a small test apparatus which functioned as a single-tube horizontal water heater. Installations were then made on tubes of two forced circulation evaporators. Ten couples were installed on the tube of an experimental evaporator having one vertical tube 12 feet (3.7 meters) long, and six couples were installed on one tube in an eight-tube semicommercial forced circulation evaporator. Consistent results have been obtained with both installations.

Both of the above tubes were calibrated in a single-tube apparatus in which it was possible to maintain constant isothermal conditions at all points over the calibration range (30° to 120° C.) with a maximum variation of $\pm 0.02^\circ$ F. (0.01° C.). The known accuracy of calibration was ± 0.001 millivolt (0.04° F. or 0.02° C.). Observed calibration values for the couples of each tube at any given temperature fell within a maximum range of 0.005 millivolt (0.18° F., 0.10° C.). Recalibration of the single-tube couples was made after 150 hours of operation. The values obtained did not diverge from the original results within the established limit of error, (0.005 millivolt = 0.18° F., 0.10° C.), and all couples were in the same relative agreement.

Results that have been achieved in the measurement of wall temperatures are well illustrated by Figure 4. This is a plot of the observed wall temperatures obtained with steam and distilled water in the 12-foot (3.7-meter) single-tube evaporator over a wide range of operating conditions. Actual couple readings, transferred to temperatures in $^\circ$ C., are plotted against the locations of the couples on the tube. (No. 5 couple was damaged during the course of a repair job on the machine. No results for this couple are reported.) Each group of curves is representative of a fixed boiling point and steam temperature. Four different velocities of circulation were employed to give the several curves.

It is difficult to adduce positive evidence of the accuracy and reproducibility of wall thermocouples. The statements made above as to the reproducibility of the readings in calibration under conditions of no heat flow are not positive evidence of the behavior of the same couples when there is a temperature gradient through the tube and films. A study of Figure 4 will show, from the relative positions of the curves in all the groups, that the couples installed by this method are apparently giving dependable readings. This is borne out by the fact that all the groups show a similar change in the curves caused by a change in velocity. Stronger evidence

(though still indirect) is the close correspondence of the curves for 10 and 13 feet (3 and 4 meters) per second. There would seem to be no error involved comparable with the accuracy of the work as a whole, when separate runs, often over a week apart and with many other runs made in the interval, will yield curves corresponding so closely as those for 10 and 13 feet (3 and 4 meters) in all the series, especially the series at 100° boiling point with steam at 110° and at 115° C.

With small over-all temperature drops only slight changes in wall temperature may be expected with changes in velocity. The curves for 80° boiling point, 90° steam, and 100° boiling point, 110° steam, indicate the close agreement that has been obtained. The very small decrease in wall temperature resulting from increasing the velocity from 10 to 13 feet (3 to 4 meters) per second for the latter set of conditions has been recorded accurately by the installed couples without a single overlapping value. Runs of the 100° boiling point, 120° steam, group were made on different days. The 3 and 10 foot (1 and 3 meter) velocities were completed a week before the 5 and 13 foot (1.5 and 4 meter) velocities were made. The 80 hours of operation conducted between those dates did not affect the consistency of the readings.

COMMENTS

The method as developed and tested in this laboratory has proved very satisfactory. A modification of the manner of withdrawal of the leads from the tube has been found possible, so that, in a purely test apparatus, the tube and thermocouples with the leads consist of a compact unit. This will make feasible a study of the effect of tube surface conditions on heat transfer coefficients, a requirement of which is the constant observation and conditioning of the tube surface. A later report will consider the modification.

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Steam-Film Heat Transfer Coefficients for Vertical Tubes

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Measurements are made of film coefficients of heat transfer for practically air-free steam condensing on the outside of a 1-inch o. d. vertical tube, 12 feet long, operated as a forced-circulation evaporator. Tube-wall temperatures are measured by a method previously described. The coefficients obtained range from about 900 to 1900 P. c. u./ (hour)(square foot)(° C.). While these values ap-

pear somewhat low on account of the relatively great length of the tube employed, they actually average 33 per cent higher than called for by the theoretical Nusselt equation. No explanation is found for this deviation, since it is felt that there is no turbulence in the condensate layer, and the constancy of the tube temperature indicates the absence of dropwise condensation.

THE larger part of the available data on heat transfer through films of condensed steam has been observed using horizontal tubes (?). Only a few workers have investigated the films on vertical tubes. Some empirical relations have been established, but generally the effort has been made to compare the data with some one of the theoretical equations that have been derived by W. Nusselt. Monrad and Badger (8) have reviewed the work on both

types of tubes. For vertical tubes they found observed values of the steam-film coefficients, ranging from 2000 to 3000 B. t. u., that were from one-half to twice as large as corresponding values calculated by the theoretical equations.

In a recent article (4), Jakob discusses his work and that of his collaborators, Erk and Eck, in comparison with the Nusselt theory for vertical tubes. He finds that, for his experiments with steam passed slowly inside of a vertical heat transfer coefficient tube, the data are in close agreement with

the theory (6). (The tube was 40 mm. in diameter and 1.20 meters long.) The results of other investigations, in which variables have been considered that are not included in the present work, also show that a theoretical correlation of the data is possible.

The shortest length of tube that would be employed in a forced-circulation evaporator is about 6 feet, and the usual length is from 8 to 10 feet. No published data can be found that concern vertical tubes of a length greater than 4 feet. Philipp (9) worked in this laboratory with tube lengths of 4, 6, and 8 feet. In only one set of his runs was it possible to obtain consistent results. The individual coefficients obtained by him for steam were much higher than corresponding values which were calculated using the Nusselt theory.

The mathematical relationship derived by Nusselt for the case of vapor condensing on a smooth vertical surface, assuming that the vapor is pure and saturated and relatively stationary with respect to the condensate is:

$$h_s = 0.943 \left(\frac{k^3 \rho^2 g \lambda}{L \mu (\Delta t_s)} \right)^{0.25} \quad (1)$$

where g = gravitational constant, (ft.)/(hr.)
(hr.) = 4.18×10^8

h_s = steam film, P. c. u./ (hr.)(sq. ft.)
(° C.)

L = length of tube, ft.

k = thermal conductivity of condensate,
P. c. u./ (hr.)(sq. ft.)(° C./ft.)

ρ = density of condensate, lb./cu. ft.

λ = latent heat of condensation,
P. c. u./lb.

μ = viscosity of condensate, (lb.)/(ft.)
(hr.) = 2.42z

z = viscosity, centipoises

Δt_s = temp. drop across condensate film,
° C.

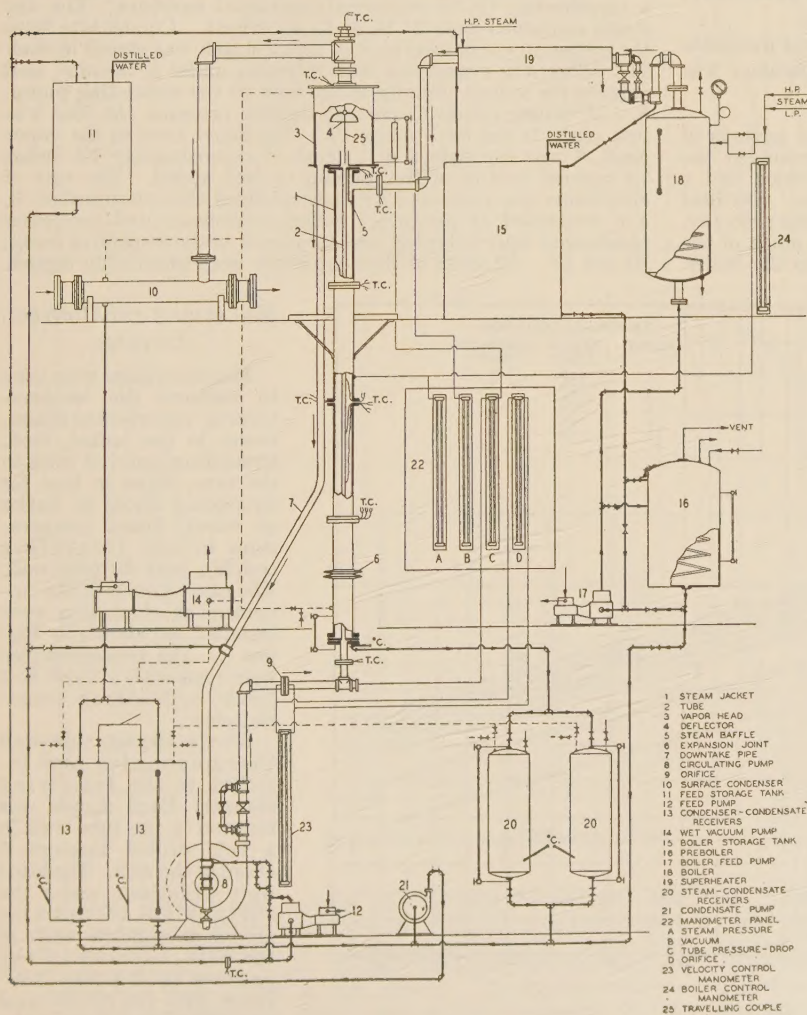


FIGURE 1. DIAGRAM OF APPARATUS

[The derivation of Nusselt's equation is given in English by Monrad and Badger (8) and Colburn and Hougen (2).]

The possibility exists that serious errors have been made in past determinations of tube-wall temperatures. This factor alone is sufficient to account for the unreliable character of many data. An accurate method for the measurement of tube-wall temperatures has been devised by Hebbard and Badger (3).

The present investigation was conducted for the purpose of obtaining information bearing on the characteristics and heat transfer coefficients of steam condensate films occurring on the tubes of vertical forced-circulation evaporators. The results, of course, have a fundamental application to the theory of heat transfer.

THE EXPERIMENTAL EVAPORATOR

The fundamental theory of Nusselt assumes conditions that may be employed as criteria in the design and operation of the experimental evaporator. These are: The steam used must be saturated and pure, and must move past the evaporator tubes at a low velocity; the outer tube surfaces must be smooth and clean, and the normal flow of the steam condensate down the tubes must not be disturbed. The physical properties of the condensate are to be taken at the arithmetic film temperature.

When this work was initiated, no equipment was available that fully met the requirements. A new apparatus was designed and assembled as shown in Figure 1:

The steam jacket, 1, constructed of four flanged sections of 6-inch i. d. standard pipe, each 3 feet long, surrounded the 1-inch eleven-gage copper experimental tube, 2, which had a length of 12 feet exposed between the tube sheets. Distilled water for the boiler, 18, was first passed through the preboiler, 16, where it was boiled continuously to remove as much of the dissolved gases as possible before it was pumped to the boiler.

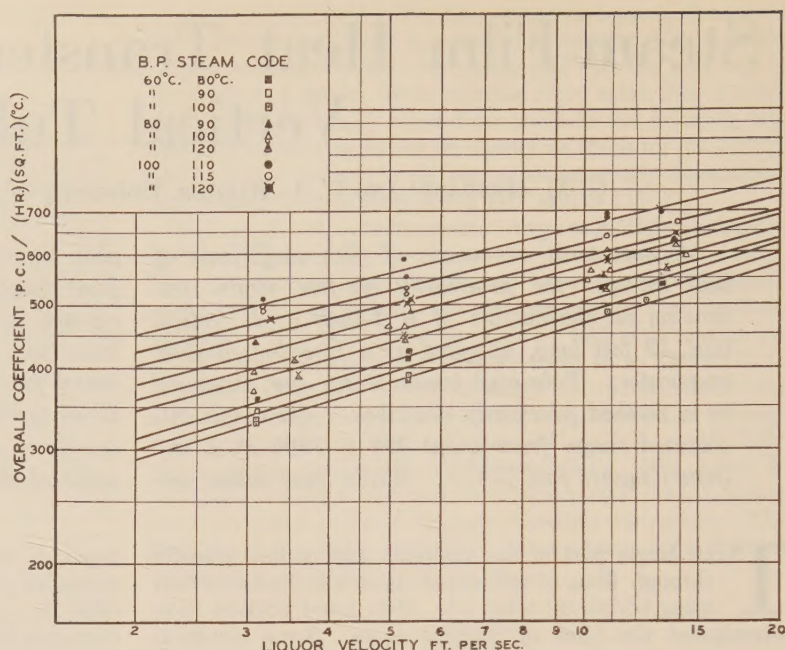


FIGURE 2. OVER-ALL COEFFICIENTS vs. VELOCITIES OF CIRCULATION

The boiler was heated by steam from the university main. The steam to the jacket was passed first through a separator and then a superheater, 19, to remove all entrained moisture. The dry steam contained from 2° to 4° C. superheat. Condensate from the evaporator was used as feed liquor which was stored in tank 11. When the evaporator was operating under a vacuum, feed entered the system directly at the inlet to the circulating pump, 8. At boiling points above atmospheric pressure, the feed was first piped to the feed pump, 12. The liquor level in the vapor head, 3, was maintained at a depth of approximately 4.5 inches by manual control of the amount of feed added. The rate of circulation was measured by a sharp-edged thin-plate orifice, 9, and controlled at pump 8. Steam condensate and condenser condensate were collected and measured in the respective tanks, 20 and 13. All parts of the evaporator were thoroughly lagged.

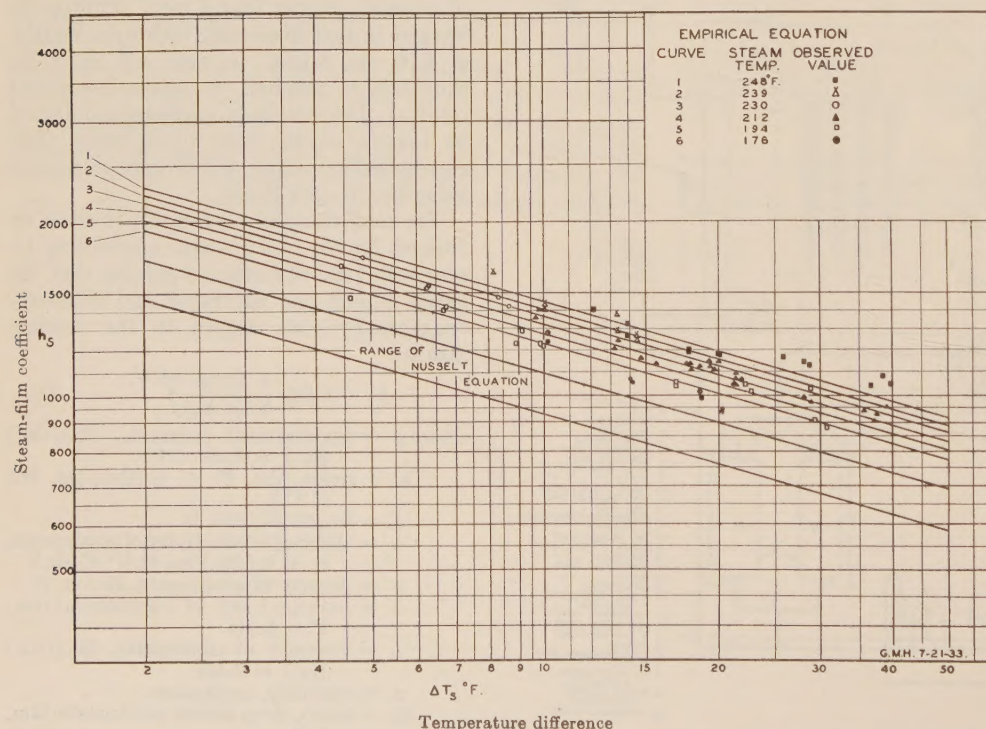


FIGURE 3. STEAM-FILM COEFFICIENT vs. TEMPERATURE DIFFERENCE

MEASURING AND CONTROL DEVICES

Thermocouples were used to measure the temperatures of: superheated steam, steam in the jacket, feed, circulating liquid at inlet to the tube, vapor in heat (or circulating liquid at outlet to tube), liquid temperatures in tube (traveling couple), and the tube wall. The exact points of the apparatus at which they were installed are shown in Figure 1. The thermocouples were read with a Type K-2 Leeds & Northrup potentiometer.

Briefly, the ten tube-wall thermocouples were installed in the following manner: Each couple was inserted in the tube wall in a hole drilled through a chord of the wall. The leads were withdrawn under the surface to an annular groove at opposite ends of the hole, carried in the groove to a point 180° from the junction and brought out from the wall together. The ther-

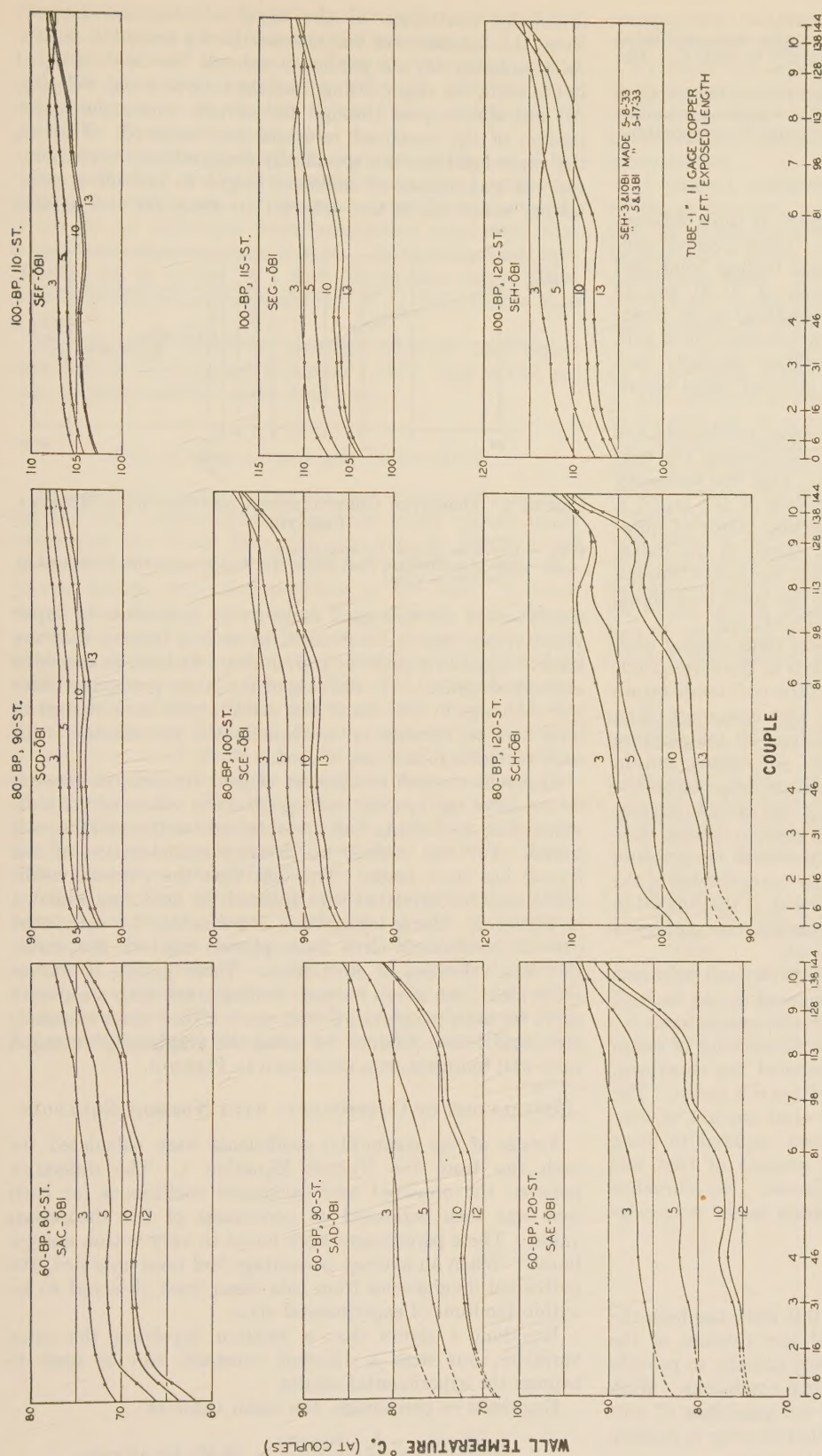


FIGURE 4. RESULTS ACHIEVED IN MEASUREMENT OF WALL TEMPERATURES

mocouple junction was brought into metallic contact with the wall by means of solder which was inserted in a plug hole drilled in the wall at right angles to and intersecting the chord hole at the middle of the latter. Special Bakelite resin was used to insulate the leads and fill in each groove. The finished installations were free from the usual causes of heat conduction to the junction and did not disturb the steam film.

The tube couples were calibrated after the evaporator tube

and condensate in the condenser-condensate receivers.

The primary temperature standard used for calibration of all thermocouples except the tube couple was a Leeds & Northrup platinum resistance thermometer. This thermometer was calibrated in the manner specified by the Bureau of Standards (1). The equation derived from the calibration data for the thermometer was checked and found to be accurate within a limit of error of less than 0.01°C. over the range from 0° to 180°C. This

was placed in the steam jacket. The apparatus was slightly modified for this procedure by the installation of the following units: a mixing section consisting of a 6×6 inch flanged nipple on the top tube sheet in place of the vapor head; a double-pipe heat exchanger in the inlet line between the circulating pump and the tube inlet; and an inlet mixing section of 6-inch pipe immediately before the tube inlet. The piping was so arranged that steam could be sent in parallel down the inside of the tube and jacket to the steam condensate tanks, and water could be circulated up the jacket and tube, the temperature of the latter being regulated by the heat exchanger. Water was used for the calibration in the range from 40° to 95°C. and steam from 100° to 130°C. When water was used, the temperature gradient up the jacket was determined by means of thermocouples installed between each pair of flanges. This gradient was small (0.1° to 0.2°C.) because of the rapid rate of circulation; and since each tube couple was calibrated against the nearest reference couple, the limit of error in calibration was small ($\pm 0.02^{\circ}\text{C.}$) After 150 hours of operation of the evaporator, the tube couples were recalibrated with steam at atmospheric pressure. The calibration values for all tube couples checked the original values at this point within a limit of error 0.1°C.

Liquor temperatures inside the evaporator tube were measured with a thermocouple installed in a 0.25-inch o. d. nickel tube 16 feet in length. The couple junction was placed at one end of the small tube, the leads being withdrawn through it to the opposite end. This small tube was inserted in the evaporator tube and was moved manually to any desired point. It was brought out of the evaporator through a stuffing box in the tee on the vapor head. The lead wires and the tube were held taut and carried upward by an arrangement of wires, pulleys, and counterweights located on the floor above the evaporator.

Mercury thermometers were used to measure the temperatures of: steam condensate leaving the steam jacket, steam condensate in the steam condensate receivers,

thermometer was used to measure the temperature of a constant-temperature bath in which the thermocouples were calibrated at intervals of 10° C. over the range from 30° to 150° C. The limit of error of the calibration was $\pm 0.01^\circ$ C.

Open mercury manometers were installed to read the pressures in the boiler, steam jacket, and vapor head. A mercury manometer was used to measure the pressure drop through the evaporator.

EXPERIMENTAL PROCEDURE

In this work the evaporator was operated at three different boiling points: 60°, 80°, and 100° C. Three over-all temperature drops were employed with each boiling point, and four velocities of circulation, approximately 3, 5, 10, and 13 feet per second, were used with each combination of steam temperature and boiling point. A run consisted of a continuous experiment 40 minutes in duration, generally, and the data were so taken that each 20 minutes could be calculated separately.

During the run, a one-inch depth of steam condensate was kept on the lower tube sheet instead of allowing the condensate to drain freely to the tanks. This was necessary because of the relatively large surface area of the tanks, a fact that would have involved a correction factor of questionable accuracy for condensation of steam in the tanks. Noncondensable gases were removed from the jacket through a vent located about 10 inches above the lower tube sheet, by continuous venting of a small quantity of steam.

All tube thermocouples were read three times during each run. The liquor temperatures were taken at the corresponding points with the traveling couple. The wall temperature at any couple position did not vary in any case more than $\pm 0.1^\circ$ C. during a run. With small over-all temperature drops (10° C.) the tube couples checked consistently within 0.02° to 0.04° C. The average temperature drops across the steam film were calculated by arithmetic and graphic averaging of the observed temperatures. The graphic average temperature differences were corrected for the small temperature gradients that existed between the actual outer surface of the tube and the average depth of immersion of the couples in the walls (0.074 inch). The corrected results were employed in the calculation of the film coefficients.

The values of the steam-film coefficients (h_s) and apparent over-all coefficients (U) have been calculated on the basis of an exposed outer tube-surface area of 3.105 square feet.

The heat input was based directly on the amount of steam condensate collected per hour and included the superheat, latent heat, and sensible heat extracted from this steam. The heat output was calculated from the total amount of condenser condensate plus the sensible heat required to bring the feed to the boiling point. The amount of feed was assumed equal to the condensate collected. No allowance was made for entrainment, and radiation losses were neglected.

RESULTS

The factor limiting the accuracy of this work has been the possible error in the measurement of the volumes of the condensates. Large tanks were installed initially to provide capacity for a wide range of operating conditions. With small over-all temperature differences the quantities of condensates collected were often so slight that an error in reading of 10 to 15 per cent could have occurred.

A study of the heat balances indicated the occurrence of considerable entrainment in the vapor from the head. This factor expressed as the percentage excess of the heat output over the heat input did not show large errors, but it was considered unwise to use the data concerning the condenser condensate for any purpose other than just a semi-quantitative check of the steam condensate data. Two facts un-

doubtedly contribute to the cause of this entrainment: First, the deflector used was necessarily of a makeshift design. As it probably did not produce a uniform "curtain" of liquid in the head, the vapor, rising from the tube at a high velocity, did not always pass through the curtain where the major portion of the entrained moisture was removed. Further, the vapor head was not specifically designed for the evaporator. It was neither of sufficient height to provide a satisfactory space above the deflector to allow for the natural

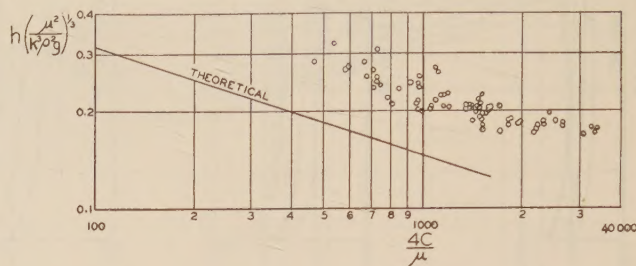


FIGURE 5 OBSERVED COEFFICIENTS COMPARED WITH NUSSULT EQUATION

$4C/\mu$ = Reynolds number for condensate

C = rate of condensate flow, lb./hr./ft. of tube perimeter (measured at bottom of tube)

separation of the entrained moisture by a decrease in vapor velocity, nor was it constructed in such a fashion that the level of liquid in it could be kept uniform without an excessive amount of control. In the case of the latter point, the effect was a change in the size of the curtain with each change in level and an increase or decrease in the vaporization with each variation in the rate of feed.

Apparent over-all coefficients of heat transfer, in general, do not have any specific bearing upon the values of the individual film coefficients that are obtained for the same experiments. For this reason, no detailed consideration of the former has been made. The fact that the over-all coefficients may be correlated with themselves, however, is shown in Figure 2. Using logarithmic coordinates, the calculated over-all coefficients have been plotted against the corresponding velocities of circulation. Three groups of curves are evident, one group for each boiling point with a separate curve for each temperature drop used. The values of steam-film coefficients, obtained by using the graphically averaged tube-wall temperatures, are shown in Figure 3.

CORRELATION OF COEFFICIENTS WITH NUSSULT EQUATION

Values of the steam-film coefficients were calculated for each run from the Nusselt Equation 1. The difference between the observed and calculated coefficients for each case was then expressed as percentage of the theoretical value. These percentages were found to vary within narrow limits. When an average percentage had been obtained, the individual divergencies from this mean were observed to be within the limit of experimental error.

Equation 1 shows that a relation involving the same variables, but with a different constant, can be used to express the experimental results.

Expressed as percentage, the mean value of

$$\frac{h_s (\text{obsd.}) - h_s (\text{Nusselt})}{h_s (\text{Nusselt})} = 33.5\% \text{ for all runs}$$

The empirical equation is:

$$h_s = 1.27 \left(\frac{k^3 \rho^2 g \lambda}{L \mu \Delta t_s} \right)^{0.25} \quad (2)$$

When the coefficients were recalculated by this equation, in no case was the deviation of the calculated from the

observed values over ± 12 per cent for any one run; and the average deviation for all runs was $+2$ per cent.

A correlation of the results of the present investigation with the theoretical equation is evidently possible. The question arises as to whether or not such a correlation is specific to the present apparatus.

A current project in this laboratory has made use of the same method of wall temperature measurement employed here in an investigation of the steam- and liquor-film coefficients for an eight-tube forced-circulation evaporator that was concentrating sucrose solutions. Six thermocouples were installed on an 8 foot $\times$ 1 inch eleven-gage copper tube. The remaining tubes were eight foot $\times$ $7/8$ inch sixteen-gage copper.

The observed coefficients averaged 60.8 per cent higher than values predicted by Equation 1, with only a few per cent deviation between individual sums.

WALL TEMPERATURES AND TURBULENCE

As previously stated, it was felt that information concerning the wall temperatures of the tube would explain much concerning the steam film. To this end, in Figure 4 the observed wall temperatures for the last half of each run were plotted against respective positions on the tube. A curve was drawn through the plotted data of each run. These curves were grouped according to the temperature drops used. A definite and orderly form was immediately noticeable in each group of curves. The wall temperature decreased with distance from the upper tube sheet. As the liquor velocity was increased, the temperatures were lowered in proportion at all points except for an irregularity displayed in several cases at the upper part of the wall, when a 3-foot velocity was used. The latter divergences from the general form of the curves are reproducible in each case, but, as a discussion of them must consider a study of conditions inside of the tube, they are left for another paper.

Jakob and Erk (5) working with a vertical tube, 0.466 meter (1.529 feet) in length, found that at high temperature differences the tube temperature first decreased, then increased at some point down the tube, and finally decreased slightly. A similar observation was made with the tube of the 8-foot evaporator previously mentioned, except that the last temperature decrease was usually quite large and

brought the wall temperature at the bottom to a point several degrees below that of the top.

Evidently the occurrence of uniform and cyclic variations in wall temperature was not previously noted by other investigators, either because of the length of tube used or because of the inadequacy of the method of wall temperature measurement.

As pointed out by Monrad and Badger (8) from their results on diphenyl, turbulence in the condensate film would lead to increasing coefficients with increasing temperature differences (or other factors tending to increase the rate of condensate flow). To determine whether this effect is of importance in this present work on steam the results have been plotted in Figure 5 (supplied by T. H. Chilton and A. P. Colburn), using the dimensionless groups called for by the Nusselt theory, as related to the Reynolds number of the condensate film. It is observed that the points, in general, lie in a band parallel to the line representing the Nusselt equation, but somewhat higher. Since turbulence is not likely below values of $4C/\mu$ of 2500, this factor cannot explain the higher values obtained. Moreover, the present results might be expected to be low on account of a thin layer of iron oxide found upon examining the tube after the experimental runs. The conditions under which turbulence may be expected to begin cannot be stated from the results of this present work. A more thorough examination of conditions with tubes of different lengths and temperature differences is necessary.

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